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(54) Title: AN OPTICAL SWITCH USING COLLIMATED ARRAYS WITH NON-COLLINEAR BEAMS

(57) Abstract: An optical switch using collimated arrays with non-collinear beams is disclosed. In one embodiment, the switch includes three or more bi-directional optical input and output ports, three or more moveable mirrors to optically connect the input and output ports, three or more collimating lenses that produce approximately collimated beams, so that the distance between two or more beams decreases as the beams propagate from the collimating lenses to the moveable mirrors.

# AN OPTICAL SWITCH USING COLLIMATED ARRAYS WITH NON-COLLINEAR BEAMS

## FIELD OF INVENTION

The present invention pertains to the field of micro-electro-mechanical-system (MEMS) devices. More particularly, the present invention relates to a MEMS mirror device.

## BACKGROUND OF THE INVENTION

A MEMS device is a micro-sized mechanical structure having mechanical circuitry fabricated, for example, by using conventional integrated circuit (IC) fabrication methods. One type of MEMS device is a microscopic gimbaled mirror device. A gimbaled mirror device includes a mirror component, which is suspended off a substrate, and is able to pivot about two axes. Motion may be caused by electrostatic actuation. Electrostatic actuation creates an electric field that causes the mirror component to pivot. By allowing the mirror component to pivot in two axes, the mirror component is capable of having an angular range of motion in which the mirror component can redirect light beams to varying positions across a two-dimensional surface.

**Figure 1** shows an example of a MEMS gimbaled mirror device used to redirect light beams in an optical switch. Light beams from fibers 1 located in input fiber array 2 are input to the optical switch and travel through input lens array 3. Each beam is then reflected from a mirror located on input movable mirror array 4 to another mirror on output mirror array 5. The light beams then travel through lens array 6 to output fiber array 7. Thus, a given beam is switched from an input fiber of input fiber array 2 to an appropriate output fiber of output fiber array 7.

The mirrors 8 and 9 on the edge of the mirror array 4 shown in **Figure 1** need to rotate only toward the center of the array but not away from the center of the array. As a result, much of the mirror's range of motion is not used. Similarly, mirrors near the center of the array do not have to rotate as far in either direction as mirrors at the edge of the array, so the outer range of motion of the central mirrors in both directions is not used.

This overdesign in the range of motion of the mirrors a problem because the mirror array size is limited by the scanning angle of the mirrors, and the separation distance between the mirror arrays. The maximum number of mirrors in each mirror array can be increased by increasing the spacing between mirror substrates, but this increases optical loss due to diffraction.

In order to increase the maximum size of the switch without increasing the mirror scanning angle or increasing the optical loss, what is needed is a switch configuration where the mirror scanning angle requirements are approximately the same for switches in every part of the array.

## SUMMARY OF THE INVENTION

An optical switch using collimated arrays with non-collinear beams is disclosed. In one embodiment, the switch includes three or more bi-directional optical input and output ports, three or more moveable mirrors to optically connect the input and output ports, three or more collimating lenses that produce approximately collimated beams, so that the distance between two or more beams decreases as the beams propagate from the collimating lenses to the movable mirrors.

Other features and advantages of the present invention will be apparent from the accompanying drawings and from the detailed description that follows below.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention is illustrated by way of example and not limitation in the figures of the accompanying drawings, in which like references indicate similar elements, and in which:

**Figure 1** is a cross-sectional side view of a portion of one embodiment of an optical switch.

**Figure 2** shows an embodiment of a three-dimensional optical switch using movable mirrors that scan in two axes, with non-collinear input and output beams.

**Figure 3** shows another embodiment of a three-dimensional optical switch using non-collinear input and output beams.

**Figure 4** shows a non-collinear array of beams produced by offset fibers.

**Figure 5** shows a non-collinear array of beams produced by non-parallel fibers.

**Figure 6** shows a non-collinear array of beams produced by a curved fiber block.

**Figures** 7 and 8 show a non-collinear array of beams produced by an additional lens.

**Figure 9** shows one embodiment of an optical switch mirror array where the equilibrium mirror angle of each mirror varies across the array.

**Figure 10** shows an embodiment of a switch having multiple collimators based on separate monolithic fiber arrays, where group of

collimator beams are converging toward another group of collimator beams.

DETAILED DESCRIPTION

An optical switch using collimated arrays with non-collinear beams is disclosed. In one embodiment, the switch includes three or more bi-directional optical input and output ports, three or more moveable mirrors to optically connect the input and output ports, three or more collimating lenses that produce approximately collimated beams, so that the distance between two or more beams decreases as the beams propagate from the collimating lenses to the movable mirrors.

An advantage of the optical switch that uses non-collinear beams is reducing the scanning angle required by the movable mirrors to optically connect the input and output ports. This efficient design of the mirrors enables the size of the mirror arrays to be increased, to allow more mirrors to be placed in the mirror arrays. This increase in the number of mirrors enables more input and output ports to be optically connected. Furthermore, the increase in the number of mirrors and optical ports is achieved without increasing the separation distance between the mirror arrays, thus eliminating the losses caused by diffraction in other attempts to increase the mirror array size by increasing the separation distance.

**Figure 2** is an illustration of an exemplary optical switching system 10 for practicing the invention. For example, optical switching system 10 may represent a 3-dimensional optical switching system. A 3-dimensional optical switching system allows for optical coupling between input fibers and output fibers in different planes using lens arrays and mirror arrays. The lens arrays and mirror arrays provide

proper angle and position of light beams traveling from input fibers to output fibers. That is, a light beam must leave and enter a fiber in a direct path. Thus, using the optical switch shown in **Figure 2**, any optical input can be connected to any optical output through the mirror arrays 20A and 20B, which contain mirrors that can be rotated along two axes.

Referring to **Figure 2**, optical switching system 10 includes input fiber array 40, input lens array 30A, input MEMS movable mirror array 20A, output MEMS movable mirror array 20B, output lens array 30B, and output fiber array 60.

Input fiber array 40 provides a plurality of optical fibers 50 for transmitting light to input lens array 30A. Input lens array 30A includes a plurality of optical lenses, which are used to collimate and direct beams of light from input fiber array 40 to individual MEMS mirror devices on MEMS input movable mirror array 20A. MEMS input movable mirror array 20A includes a plurality of electrically addressable MEMS mirror devices 100.

MEMS mirror device 100 may be a gimbaled mirror device having a rectangular shape. Alternatively, MEMS mirror device 100 may be a gimbaled mirror device having an elliptical or circular shape. The plurality of MEMS mirror devices 100 for MEMS input movable mirror array 20A can pivot a mirror component to redirect or reflect light to varying MEMS mirror devices on second MEMS mirror array 20B. MEMS output movable mirror array 20B also includes a plurality of MEMS mirror devices such as MEMS mirror device 100, which are used to redirect and reflect light beams to varying lenses on output lens array 30B. Output lens array 30B collimates and focuses beams of light from output mirror array 20B to individual output fibers 70 of output fiber array 60.

Optical switching system 100 allows light beams from any input fiber 50 of input fiber array 40 to be redirected to any output fiber 70 of output fiber array 60. For example, a light beam following the path "A" is outputted from one input fiber and is redirected using MEMS movable mirror arrays 20A and 20B to a different output fiber. The MEMS movable mirror arrays may also be used in scanning systems, printing systems, display systems, and other systems that require redirecting beams of light.

As the light beams travel from first lens array 30A to first MEMS mirror array 20A, the light beams converge toward the center of mirror array 20A. Because the light beams are non-collinear and converging as they approach mirror array 20A, the scanning angle required by mirrors in array 20A are reduced compared to the scanning angle required by mirrors in prior art switches. Thus, the size of mirror array 20A can be increased and have more mirrors than prior art mirror arrays. The size of the other components, including mirror array 20B and fiber arrays 40 and 60 can thus also be increased.

**Figure 3** is a cross-section of the three-dimensional optical switch using non-collinear input and output beams shown in **Figure 2**, where only the mirror arrays 20A and 20B are shown for clarity. The beams from the edges of the lens array are angled toward the center, so that every mirror only has scan equally in either direction. In this embodiment, the spacing between the fibers is increased relative to the spacing between the mirrors, so that the beams are converging as they travel from the input fibers 50 towards the mirror array 20A. To achieve this geometry, the lens pitch, or the spacing between lenses, may not be constant.

Figure 4 shows an embodiment of an apparatus that generates a collimated non-collinear converging array of light beams. Fiber input block 40 contains optical fibers 50. Light beams are output from the fibers 50 and are received by lens array 30A. The light beams are approximately collimated by lens array 30A and are output through lenses 31A.

The spacing distance 460 between fibers 50 is greater than the spacing distance 470 between lenses 31A. As a result, each beam travels through a corresponding lens 31A at a different portion of the lens. Therefore, the output light beams from lens array 30A are non-collinear and converging as the beams approach the mirror array. As a result, the scanning angles of the first mirror array 20A can be reduced or equalized, so that each mirror in the first mirror array 20A does not scan through an angle that is greater than the angle required to direct a light beam from a mirror in the center of array 20A to any mirror in the second mirror array 20B.

Figure 5 shows an alternative embodiment of an apparatus that generates a collimated non-collinear converging array of light beams. Fiber input block 40 contains optical fibers 50. Light beams 530 are output from the fibers 520 and are received by lens array 30A. The light beams are approximately collimated by lens array 30A and are output through lenses 31A.

Optical fibers 50 are attached to fiber input block 40 at an angle relative to the surface 32A of lens array 30A. The angle of each fiber 50 is selected so that the light beams pass near the center of the lenses to minimize lens aberration, producing an array of beams that are non-collinear and converge as they approach the first mirror array 20A. Therefore, the output light beams from lens array 30A are non-collinear

and converging as the beams approach the mirror array 20A. The scanning angles of the first mirror array can be reduced or equalized.

Another method of providing non-collinear optical beams is to polish the fibers 50 using a curved surface as shown in **Figure 6**. The fibers may also be non-collinear in this embodiment. Fiber input block 40 contains optical fibers 50. Light beams are output from the fibers 50 and are received by lens array 30A. The light beams are approximately collimated by lens array 30A and are output through lenses 31A.

The optical fibers 50 are polished using a polishing device having a curved surface 625. Thus, the light beams converge as the beams are output from the fibers 50. The beams are non-collinear and continue to converge as the beams approach the first mirror array. Therefore, the output light beams from lens array 30A are non-collinear and converging as the beams approach the mirror array. The scanning angles of the first mirror array can be reduced and equalized.

**Figure 7** shows an alternative embodiment of an apparatus that generates a collimated non-collinear converging array of light beams. Fiber input block 40 contains optical fibers 50. Light beams are output from the fibers 50 and are received by lens array 30A. The light beams are approximately collimated by lens array 30A and are output through lenses 31A.

The light beams output from lens array 30A are collinear. The light beams then travel through lens 760. Each light beam travels through a different portion of the curvature of lens 760. This causes the light beams to become non-collinear and converge as the beams approach the first mirror array 20A. An implementation of a switch using the lens 760 shown in **Figure 7** is illustrated in **Figure 8**. Another lens 860 may receive the non-collinear beams from the second mirror array 20B and

cause the beams to become collinear before the beams enter the optical fibers of the fiber output block 60, as shown in **Figure 8**.

Another embodiment of an apparatus that reduces the mirror angular tuning requirements is shown in **Figure 9**. In this embodiment, the mirrors 21 of mirror array 20 are fabricated so that the equilibrium position of each mirror is at an appropriate angle to the substrate as shown in **Figure 9**. The angular tuning requirement from the fabricated angle is approximately the same for any mirror 21 in the array 20. At the equilibrium position, each mirror 21 is tilted toward the center of the array, with the tilt increasing as the distance of the particular mirror increases from the array center.

Another approach to producing converging beams is to use multiple fiber-lens collimators 51A and 52A at different angles as illustrated in **Figure 10**. This multiple collimator technique of **Figure 10** can be combined with the other techniques illustrated earlier. For example, the output beams of each fiber-lens collimator can be converging within a group as illustrated in **Figure 4**, while the groups of beams are also converging. In this embodiment, light beams from collimator 51A converge toward the center of mirror array 20A. Also, light beams from collimator 52A converge toward the center of mirror array 20A.

In the foregoing specification, the invention has been described with reference to specific exemplary embodiments thereof. It will, however, be evident that various modifications and changes may be made thereto without departing from the broader spirit and scope of the invention as set for in the appended claims. The specification and drawings are, accordingly, to be regarded in an illustrative rather than a restrictive sense.

CLAIMS

What is claimed is:

1. An optical switch comprising:

an optical input port having a plurality of optical fibers to input light beams into the switch;

a lens array having a plurality of collimating lenses to collimate the light beams from the input ports;

an optical output port having a plurality of optical fibers to output light beams from the switch;

an array of movable mirrors to optically connect the optical fibers in the input port to the optical fibers in the output port;

wherein the distance between two or more beams decreases as the light beams propagate from the lens array to the movable mirrors, so that the light beams are non-collinear.

2. The switch of claim 1 wherein one or more of the collimating lenses is offset from the axis of its corresponding optical fiber in the input port, so that the corresponding light beam is not collinear with another light beam in the switch.

3. The switch of claim 1 wherein at least two of the movable mirrors are fabricated on one substrate.

4. The switch of claim 1, wherein the movable mirrors are movable in two axes, and the non-collinear beams reduce the angular variation of the movable mirrors.

5. The switch of claim 1, wherein the spacing between each collimating lens is not equal to the spacing between each optical fiber in the input port to generate the non-collinear light beams.

6. The switch of claim 1, wherein the optical fibers in the input port are polished by a holder with a curved polish, to generate the non-collinear light beams.

7. The switch of claim 1, wherein the non-collinear light beams are produced by offsetting the optical fibers of the input port from corresponding lenses in the lens array.

8. The switch of claim 1, wherein the non-collinear light beams are produced by non-parallel optical fibers in the input port.

9. The switch of claim 1, wherein the surface of the input port is curved, so that the non-collinear light beams are produced by the curved surface of the input port.

10. The switch of claim 1, further comprising a single lens between the lens array and the movable mirrors, so that the non-collinear light beams are generated by the single lens.

11. The switch of claim 1, wherein the equilibrium angle of the movable mirrors varies across the array of movable mirrors, so that the non-collinear light beams are generated by the varying angles of the mirrors.

12. The switch of claim 1, wherein the optical input port comprises a first array of optical fibers and a second array of optical fibers placed at

an angle to the first array, so that the light beams from the first and second fiber arrays converge as the beams approach the movable mirrors.

13. An optical switch comprising:

an optical input port having a plurality of optical fibers to input light beams into the switch;

an optical output port having a plurality of optical fibers to output light beams from the switch;

an array of movable mirrors to optically connect the optical fibers in the input port to the optical fibers in the output port;

a lens array having a plurality of collimating lenses to collimate the light beams as the beams propagate from the mirrors to the output port;

wherein the distance between two or more beams decreases as the light beams propagate from the movable mirrors to the lens array, so that the light beams are non-collinear.

14. The switch of claim 13, wherein the movable mirrors are movable in two axes, and the non-collinear beams reduce the angular variation of the movable mirrors.

15. The switch of claim 13, further comprising a single lens between the lens array and the movable mirrors, so that the non-collinear light beams are generated by the single lens.

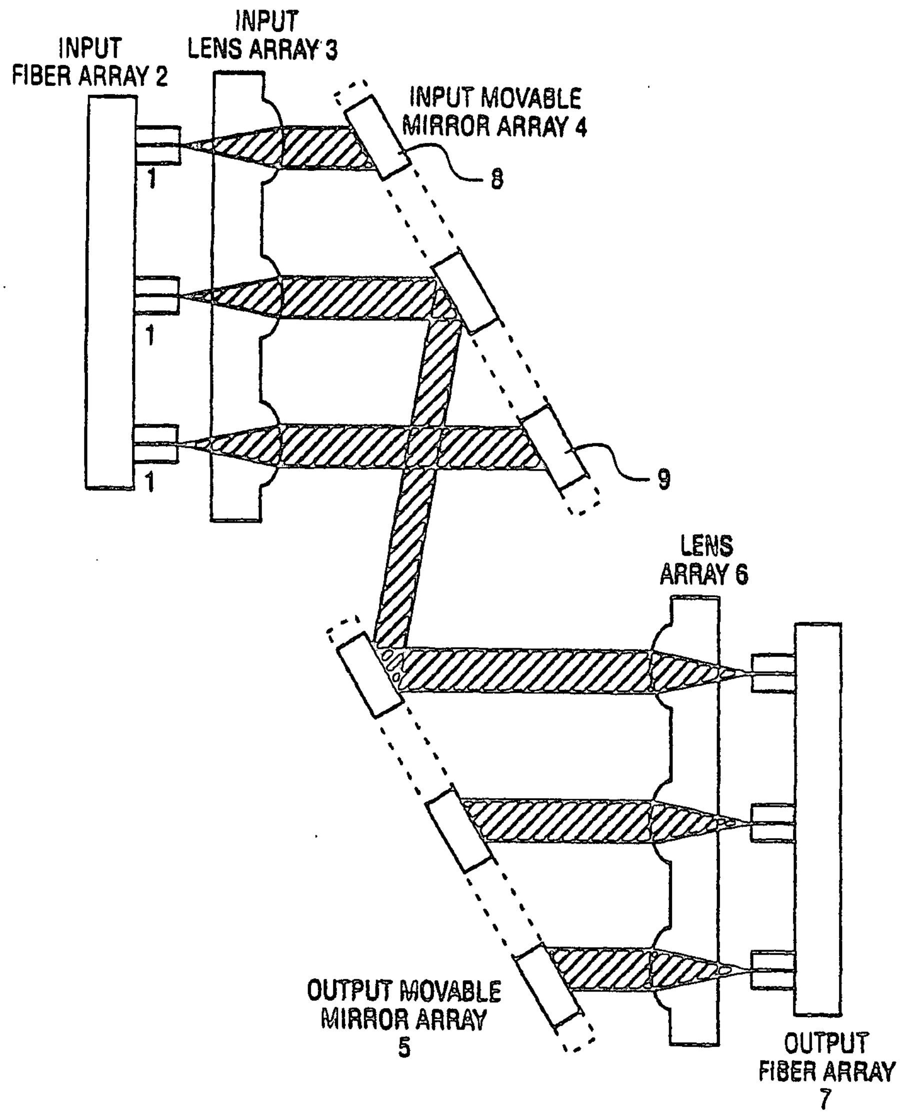
16. The switch of claim 13, wherein the equilibrium angle of the movable mirrors varies across the array of movable mirrors, so that the non-collinear light beams are generated by the varying angles of the mirrors.

17. A method comprising:

inputting light beams from an input plurality of optical fibers in an input fiber array into an optical switch having movable mirrors;

causing the light beams from the input fiber array to converge as the beams approach the movable mirrors; and

optically switching the light beams from each input optical fiber to a corresponding output optical fiber in an output fiber array.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FIBER ARRAY 2
INPUT
LENS ARRAY 3
INPUT MOVABLE
MIRROR ARRAY 4
8
1
1
1
9
LENS
ARRAY 6
OUTPUT MOVABLE
MIRROR ARRAY
5
OUTPUT
FIBER ARRAY
7

FIG 1

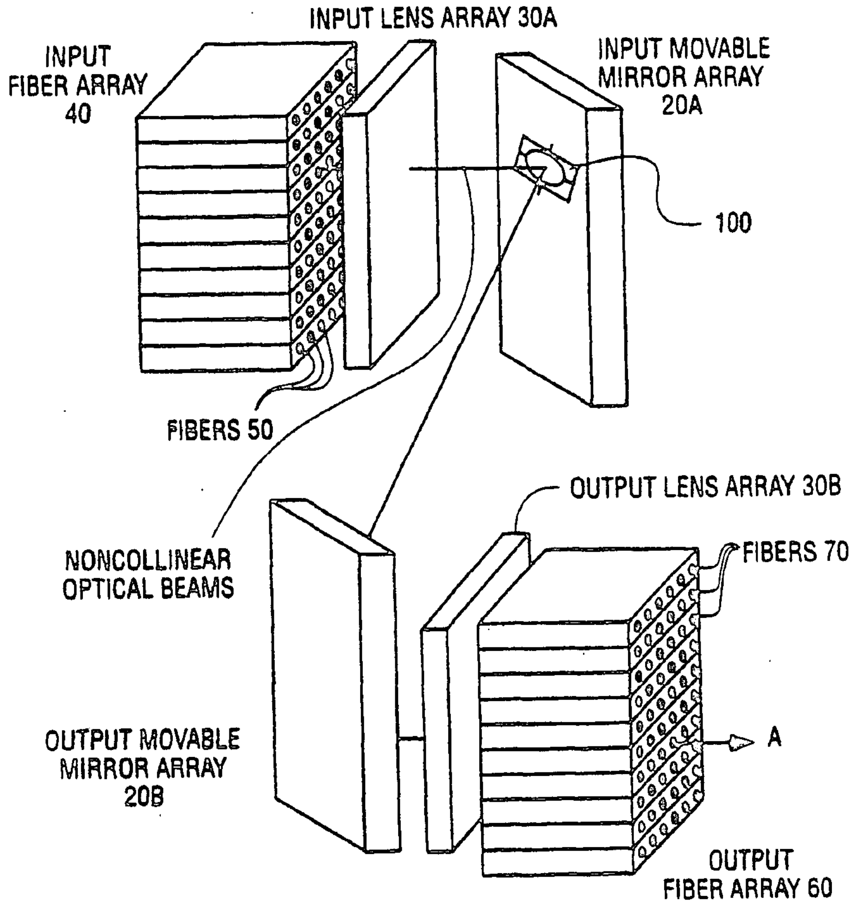
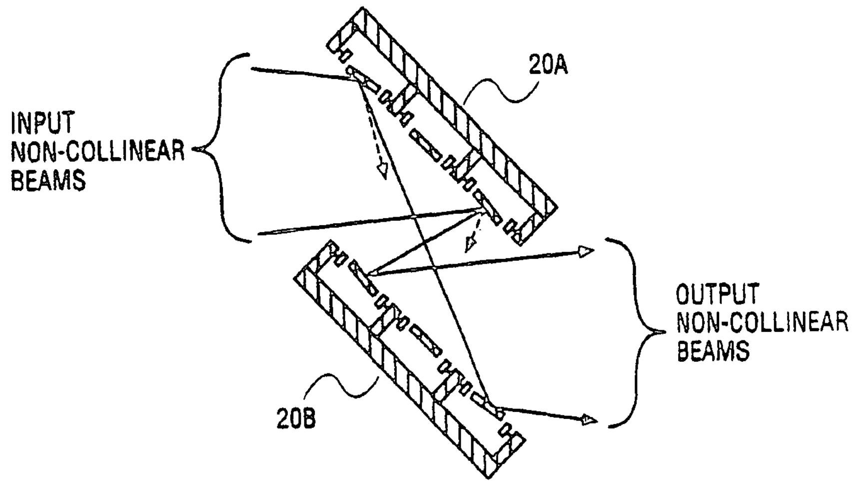

INPUT LENS ARRAY 30A
INPUT FIBER ARRAY 40
INPUT MOVABLE MIRROR ARRAY 20A
100
FIBERS 50
OUTPUT LENS ARRAY 30B
NONCOLLINEAR OPTICAL BEAMS
FIBERS 70
OUTPUT MOVABLE MIRROR ARRAY 20B
A
OUTPUT FIBER ARRAY 60

FIG. 2


INPUT
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BEAMS
20A
OUTPUT
NON-COLLINEAR
BEAMS
20B

FIG. 3

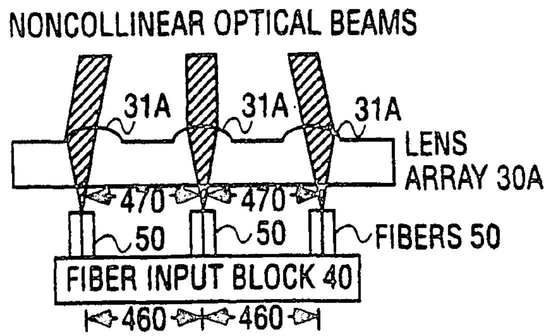


FIG. 4

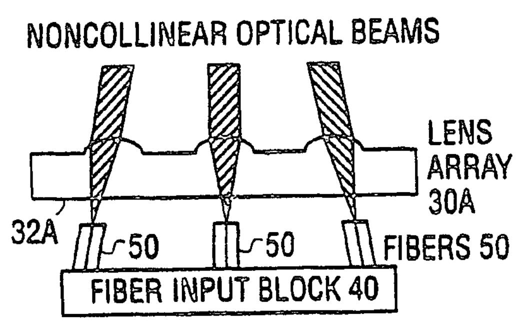


FIG. 5

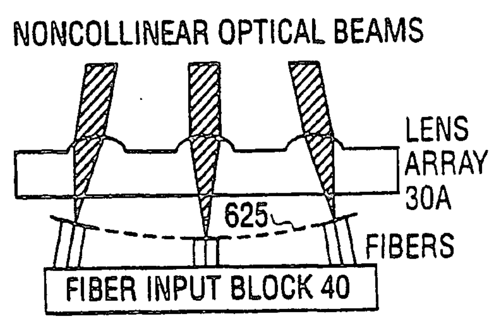


FIG. 6

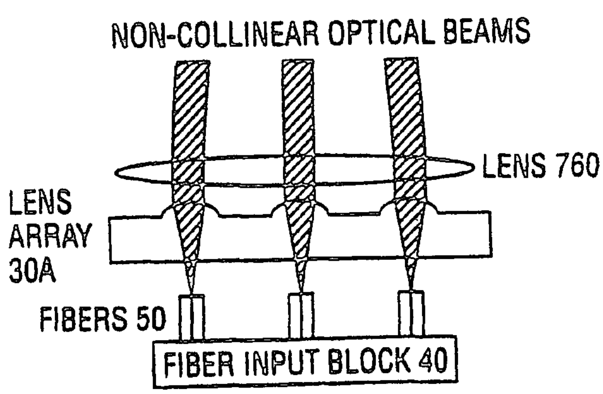


FIG. 7

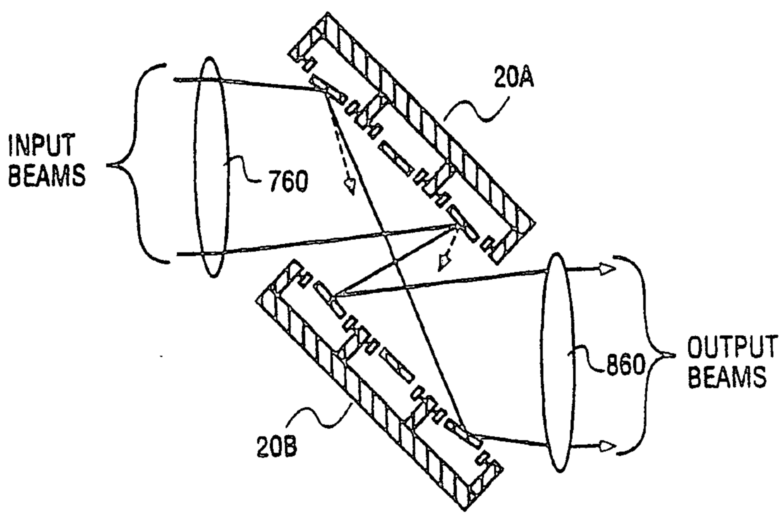


FIG. 8

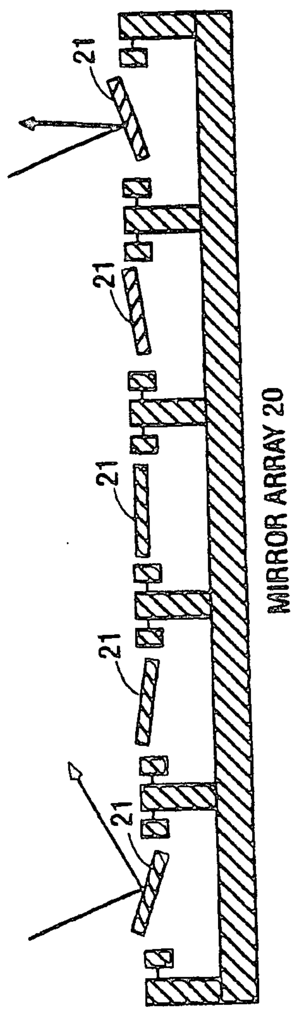


FIG. 9

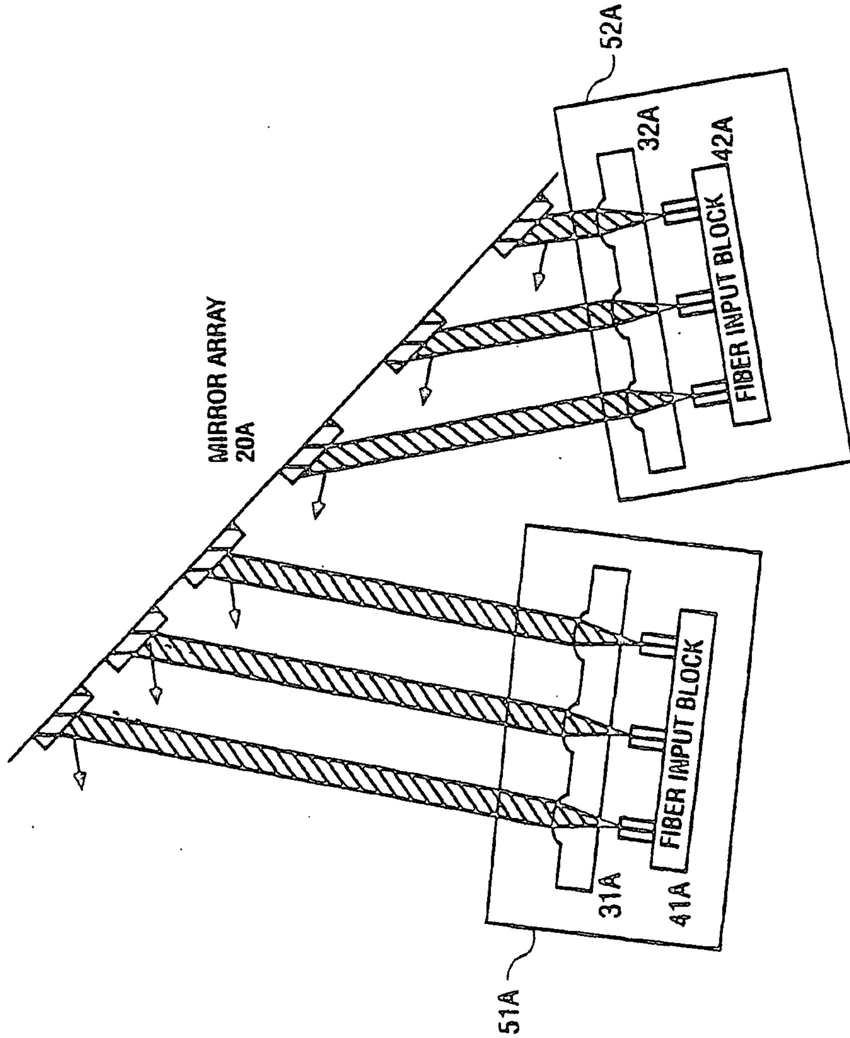
MIRROR ARRAY
20A
52A
32A
42A
FIBER INPUT BLOCK
FIBER INPUT BLOCK
31A
41A
51A

FIG. 10